THERMAL ANALYSIS METHODS
FOR AN EARTH ENTRY VEHICLE

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Outline

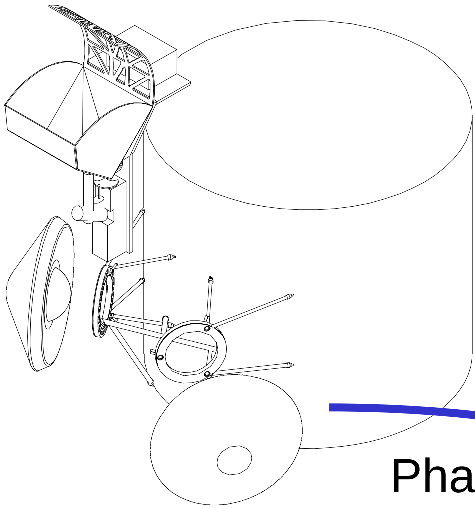
- Mission Background
- Design Description
- Thermal Modeling
- Results
- Conclusions

Mission Background

- Purpose of Mars Sample Return mission would be to return Martian sample to Earth for study
- Purpose of Earth Entry Vehicle (EEV) would be to return sample from spacecraft to Earth's surface
- Sample must be protected from entry heating and structural loads
  - Science thermal limit of 50°C on samples
  - Vehicle limits on max temperatures for structures
- Design maximizes assured containment reliability
- Many designs being evaluated; CP5.7 concept described here

Mission Phases

Phase 1
On spacecraft

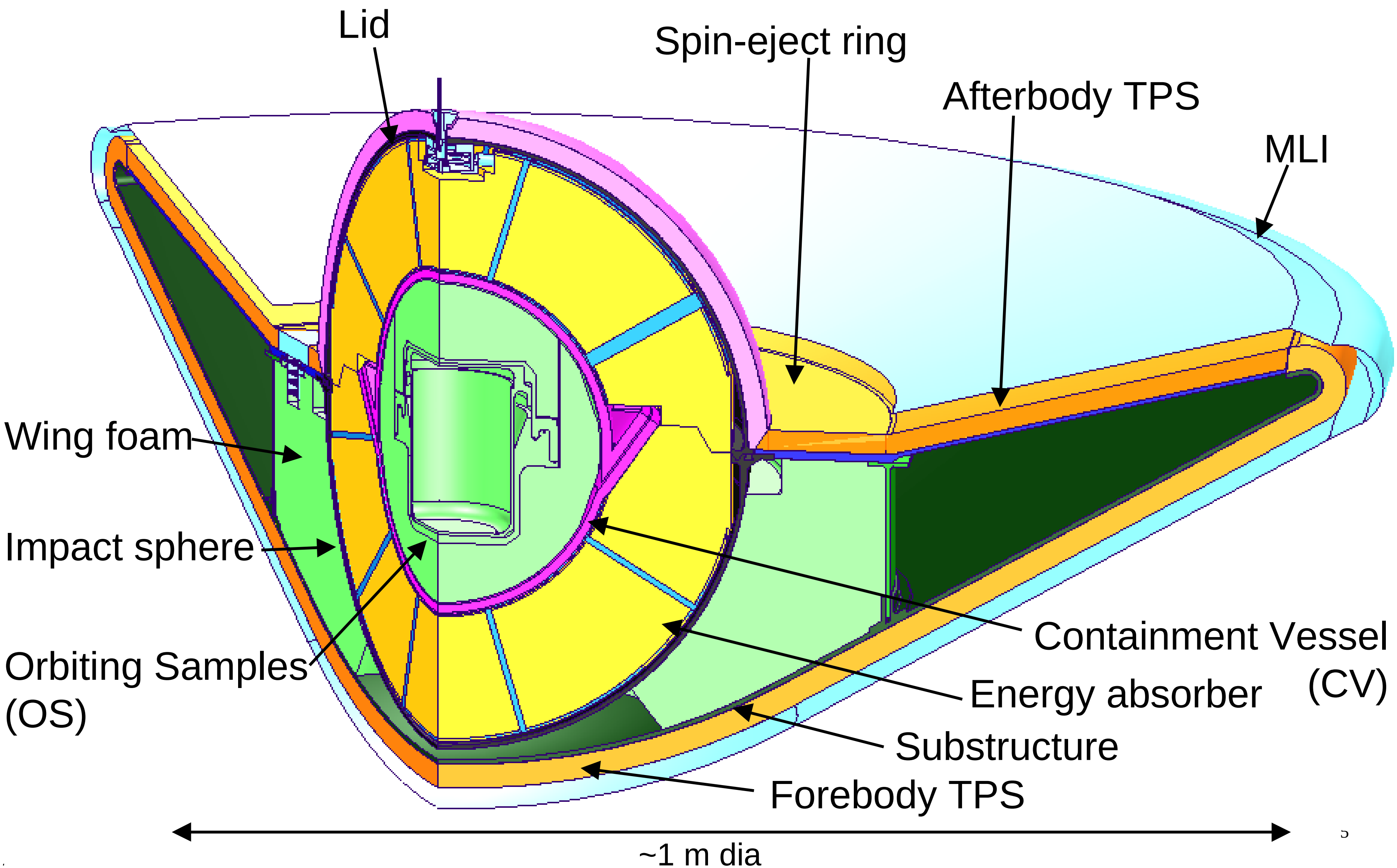


Phase 2
Release and
hyperbolic orbit

Phase 3
Atmospheric entry

Phase 4
Landed

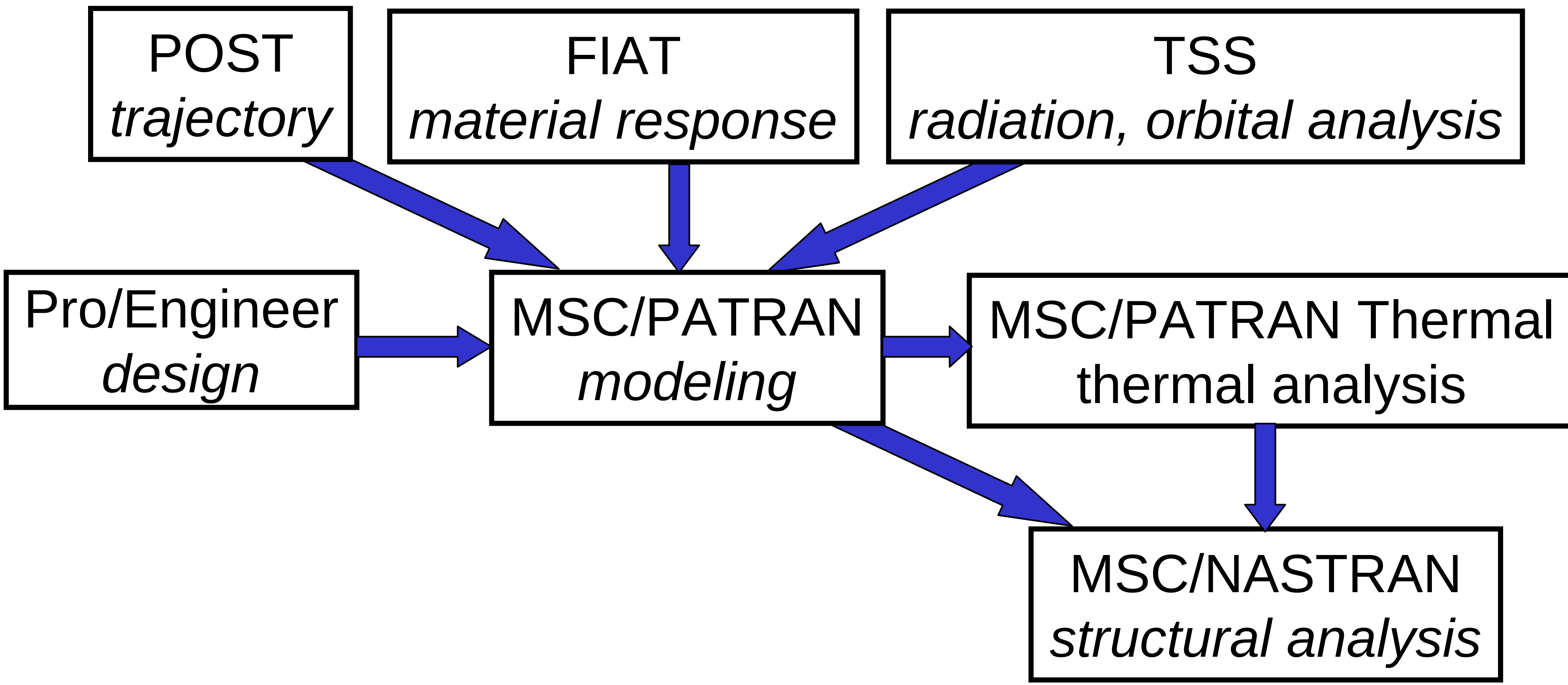
EEV CP5.7 Concept: 120° Model



Modeling Integration Challenges

- Integrate:
    - geometry from design
    - orbital analysis
    - trajectory information
    - aeroheating
    - TPS material response
    - thermal analysis with 3D orthotropic temperature dependent properties
    - structural analysis

Modeling Process



Thermal Modeling Methods

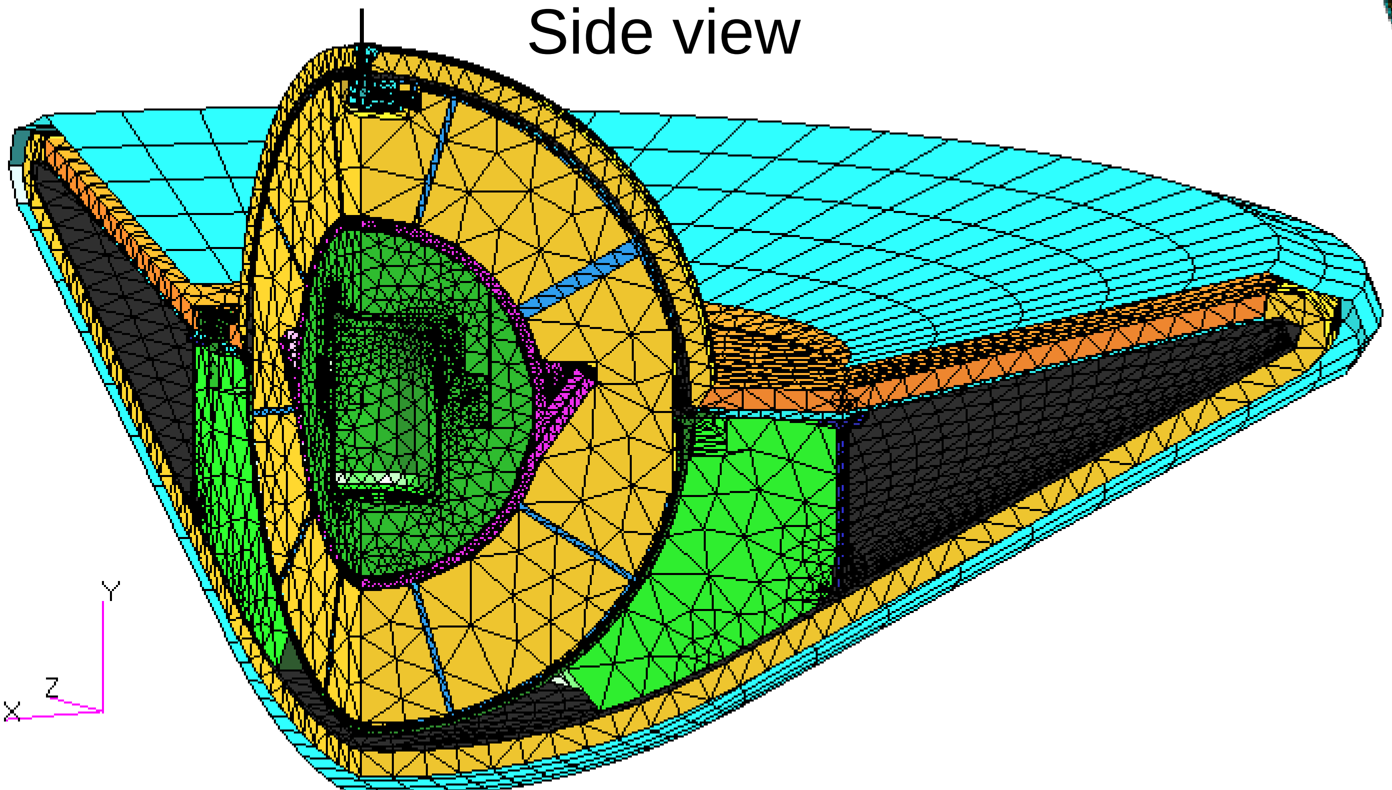
- Import geometry directly from Pro/E into MSC/PATRAN and mesh
  - Evaluate design mods by importing only changed part
  - Evaluate new design by importing and saving all materials, boundary conditions, etc.
  - Parts separated into groups
  - Minor parts (e.g., bolts) can be neglected
- PATRAN Thermal 9.0 solver
- 3D versus 2D axisymmetric evaluated
  - 3D allows non-symmetries with roughly equivalent solution time
  - 2D more time-consuming to develop
  - 120° model used
- Initial conditions for later phases imported from differing mesh
  - Temperature interpolation between different phases’ meshes internal to PATRAN

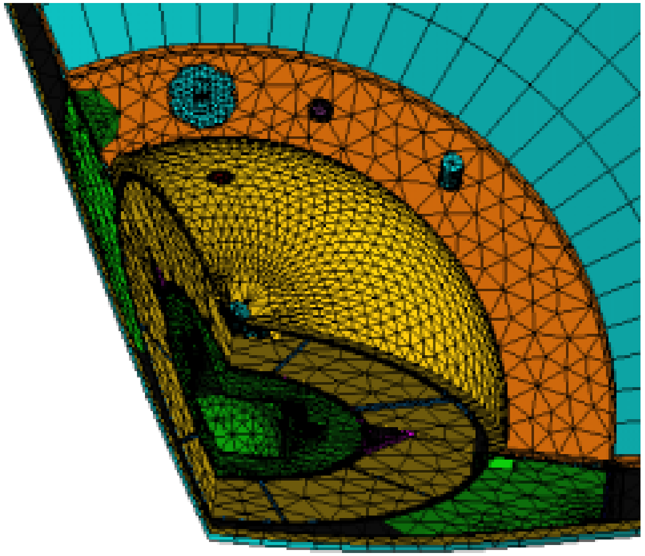
Exo-atmospheric Mesh

Exo-atmospheric and post-landing model

- Imported solids meshed directly with tets
- 50,000 nodes

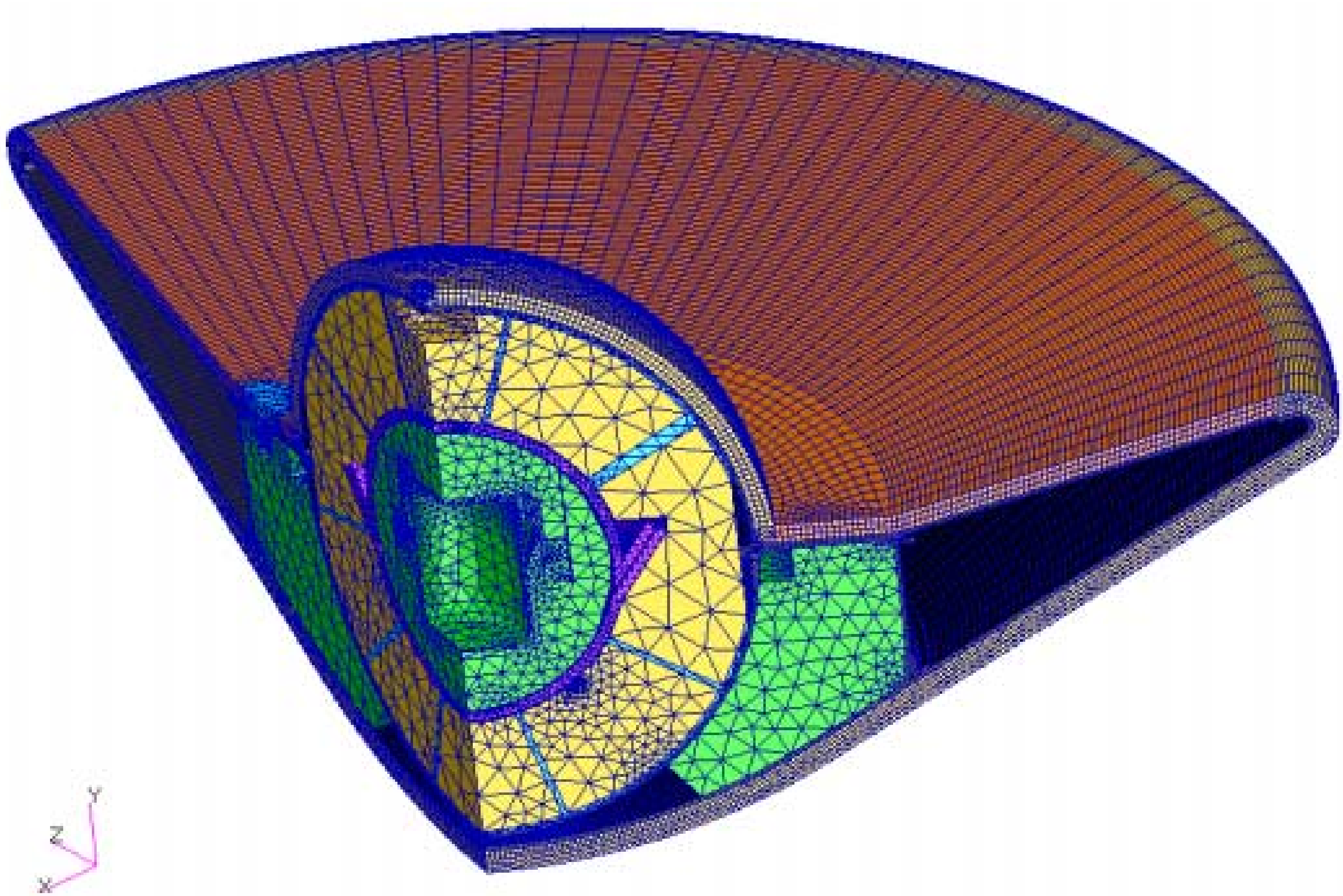
Side view





Top view

Entry Mesh



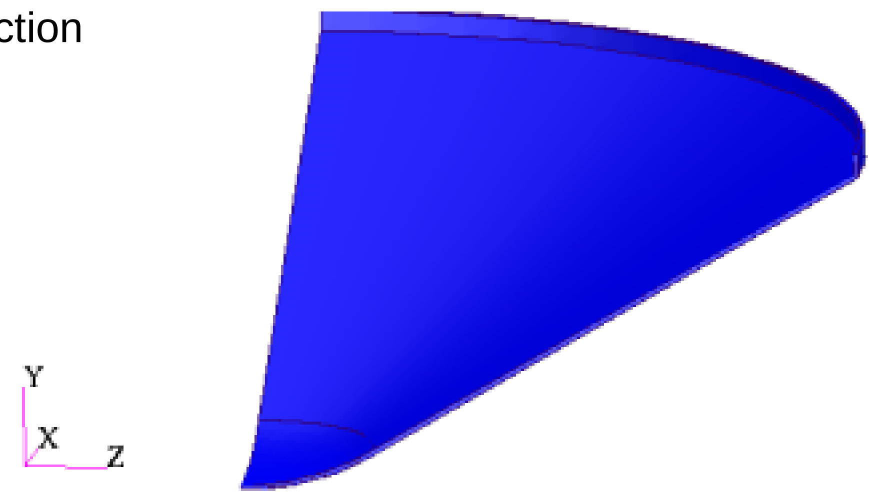
- Flux level failed solver when tets used at surface
- Imported solids cannot be directly meshed except for interior components
- Quad mesh created on side surfaces and swept through volume
- Mesh size optimized for solution convergence and time
- 180,000 nodes; density at surface 5 mm

Material Properties

- Material properties from TPSX, NASA reports, PATRAN Thermal database, vendor literature
- All thermal conductivity and specific heat as f(T)
- 3D orthotropic properties used on all fibrous materials
  - Difficulty in modeling due to varying orientation of component
  - e.g., for aeroshell, rotation of in-plane direction around x and z is changing continuously
  - Equation form for Eulerian rotation angles:

$$\phi = \sin^{-1}\left(\frac{Z}{R}\right) * \cos\left(\tan^{-1}\left(\frac{X}{Z}\right)\right)$$

where X is x-coord, Z is z-coord, and R is nose radius



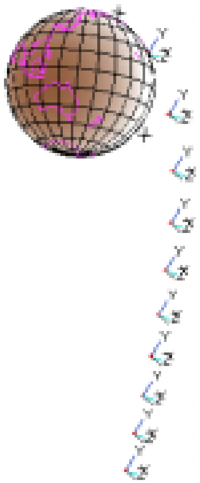
  - Each curved fibrous component required separate field equation

Radiation Modeling Methods

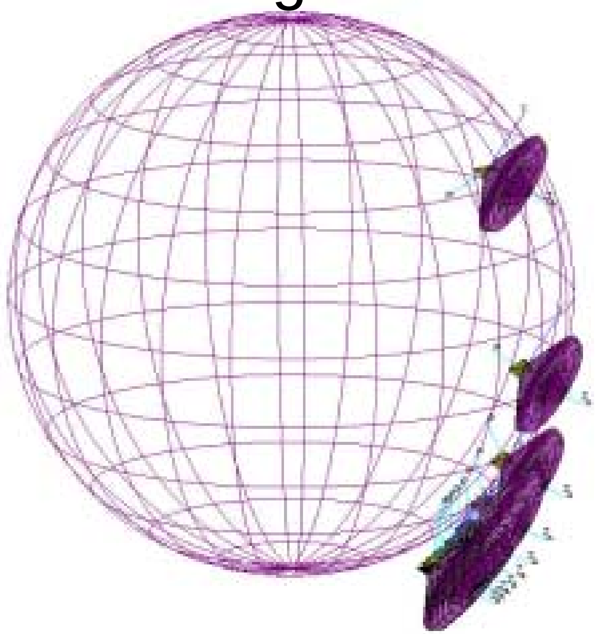
- Vehicle exterior modeled in Thermal Synthesizer System (TSS)
  - Only 6 exterior surfaces
  - Change to new design by altering only a few parameters
  - Minor effort in duplicate model development could be eliminated with translator development
- Hyperbolic orbit allowed via trajectory point input
- Dynamic orbit visualization
- Dynamic heat flux distribution visualization
- Fluxes on surfaces spin-averaged over exterior
- Radiation view factors used as input to PATRAN boundary conditions

Radiation Model Example

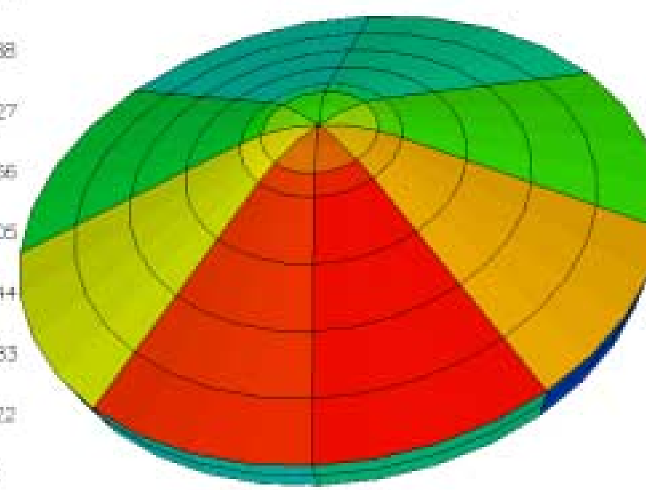
Incoming orbit steps



Incoming orbit view



Fluxes in W/m2



TFAWS 2000

Thermal Assumptions

- Contact between parts via 0.25-mm thick adhesive
- Exo-atmospheric cruise
  - Vehicle starts exo-atmospheric cruise at -80°C
  - Radiation to deep space, solar and Earth loads; solar flux and MLI on forebody
  - MLI effective emissivity $\varepsilon = 0.03$
- Atmospheric entry
  - Radiation and convection to atmosphere [temperature = f(alt) for GRAM-95]
    - MLI would break away, so TPS emissivity used
  - Convective and radiative heat pulse from aeroheating analysis
  - TPS gradient must correlate to TPS sizing analysis
- Post-landing
  - Radiation and convection to 25°C ambient

Exo-atmospheric Thermal Results (°C)

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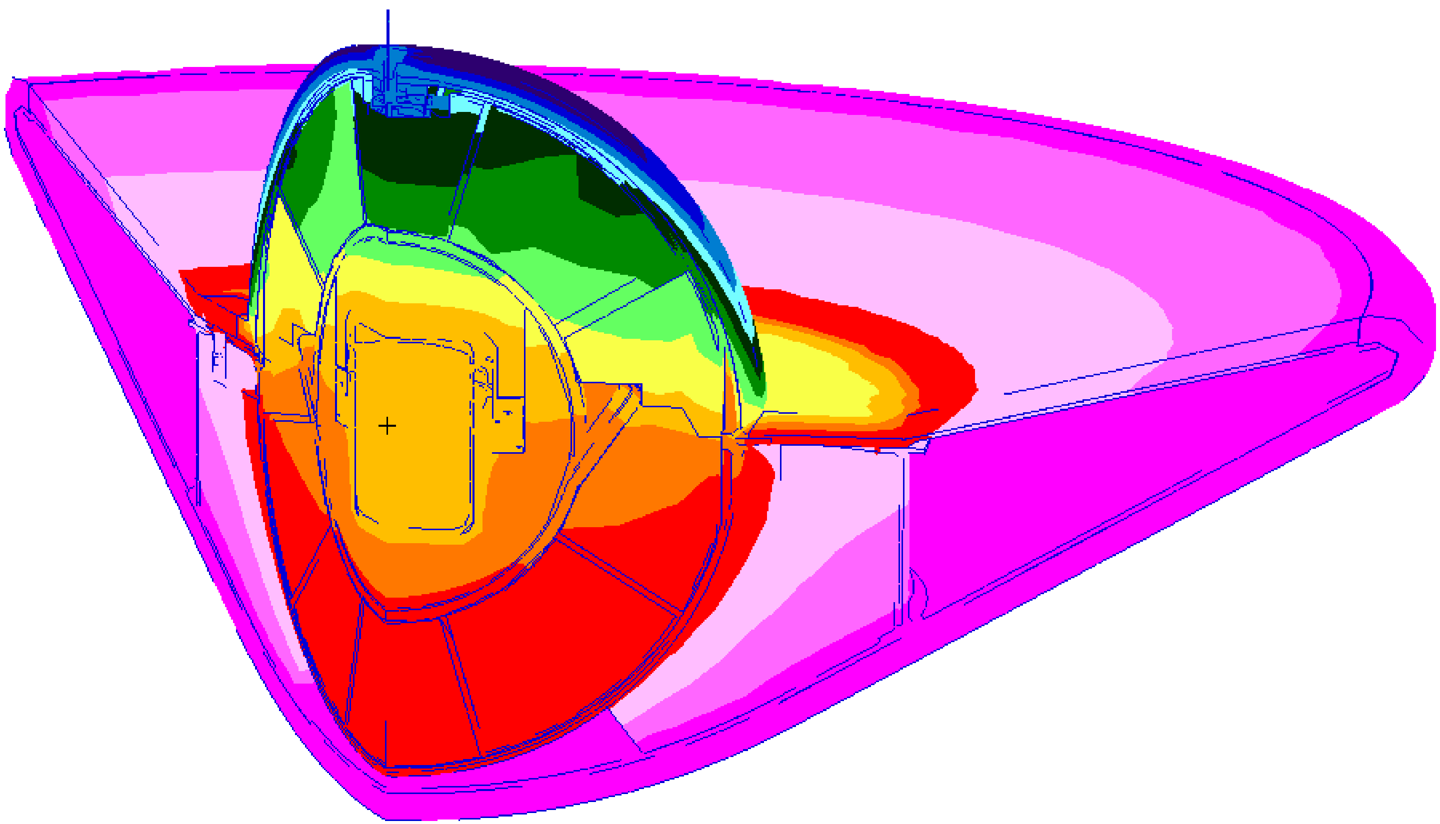
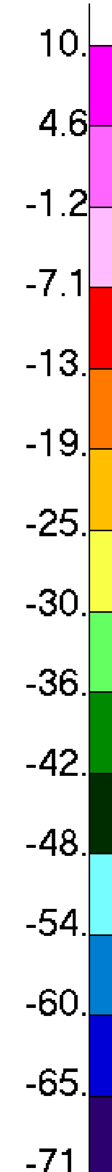
MLI α/ε=.6/.3

Lid ε=.88, S/E ε=0.58





Gradient across vehicle decreased from 116°C to 81°C by using orthotropic properties

Thermal to Structural Translation

- Normal translation straight-forward
  - map field from thermal model to structural mesh
- Structural shell models using meters require the following:
  - scale structural model to millimeters for temperature interpolation
  - rotate scaled FEM to align with thermal FEM
  - interpolate temperatures from thermal to structural model
  - thermal strain analysis using scaled, rotated shell FEM
  - combine thermal stresses with pressure loads if necessary (not shown)

Exo-atmospheric Structural Results

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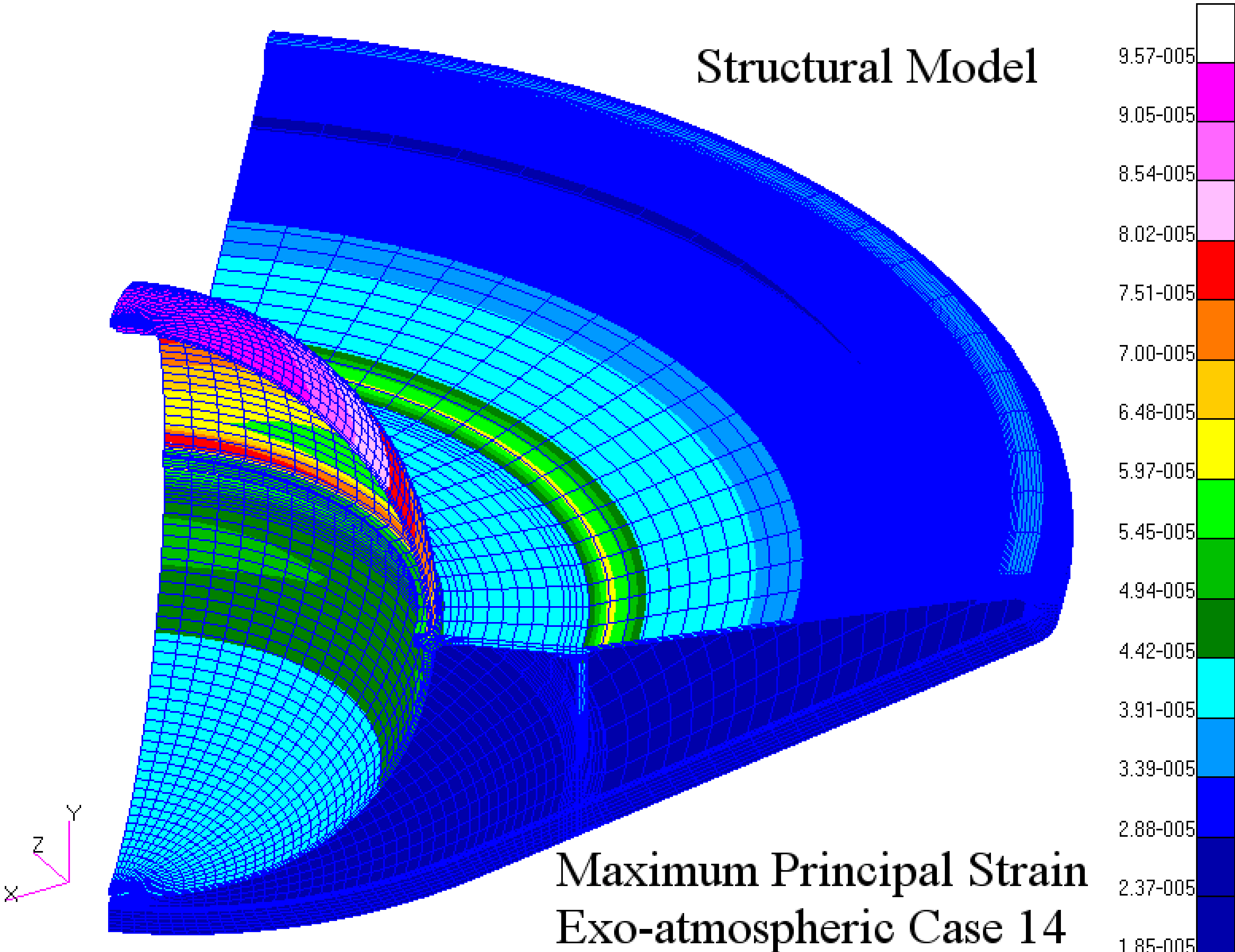
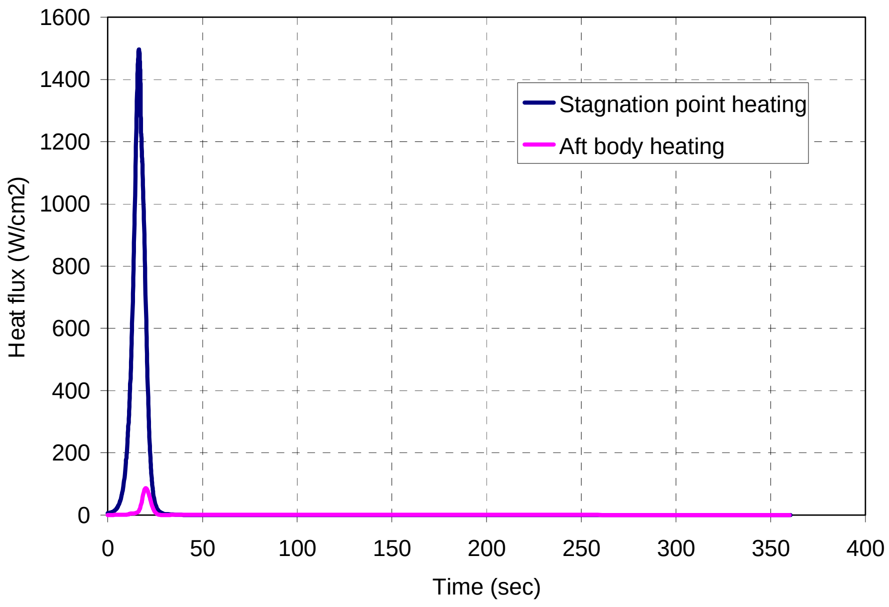
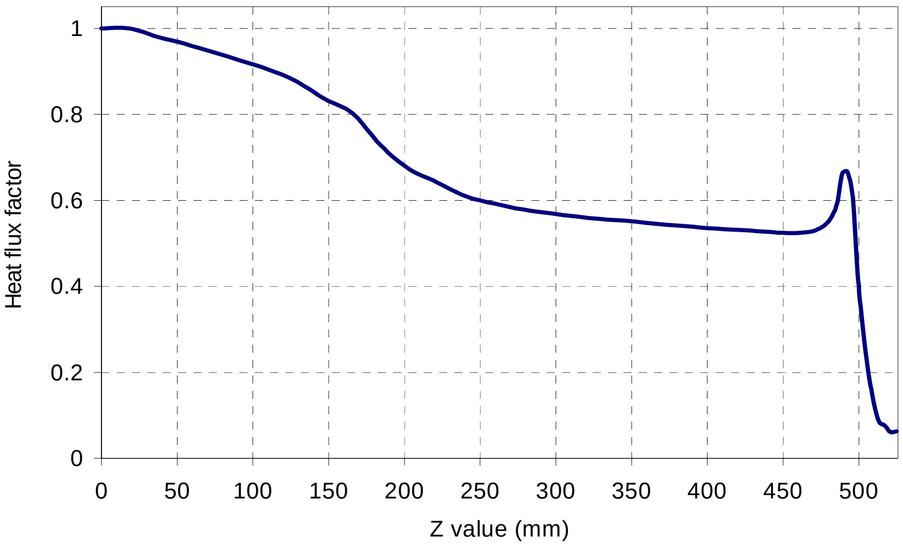


Entry Heat Pulse on Forebody

- Entry heat flux dependent on both space and time
- Time dependent flux at stagnation point multiplied by spatial factor over body

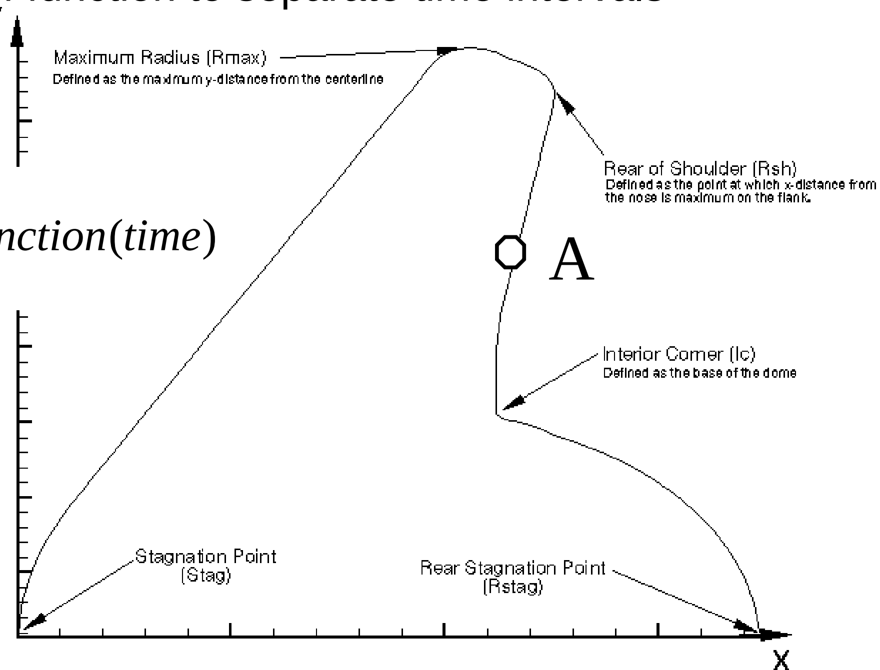




Entry Heat Pulse on Aftbody

- Heating given at three points on aftbody (Rstag, Ic, Rsh)
- Linear interpolation done between those points
  - Heating at each point is f(time)
  - Ratio of each outer point to Ic determined
  - Ratios fairly constant over three distinct time intervals
  - Interpolation done using ratios and on/off function to separate time intervals

$$Q_A = Q_{Rsh} * \left(spatial\_function \frac{Q_{Ic}}{Q_{Rsh}}(A) \right) * step\_function(time)$$



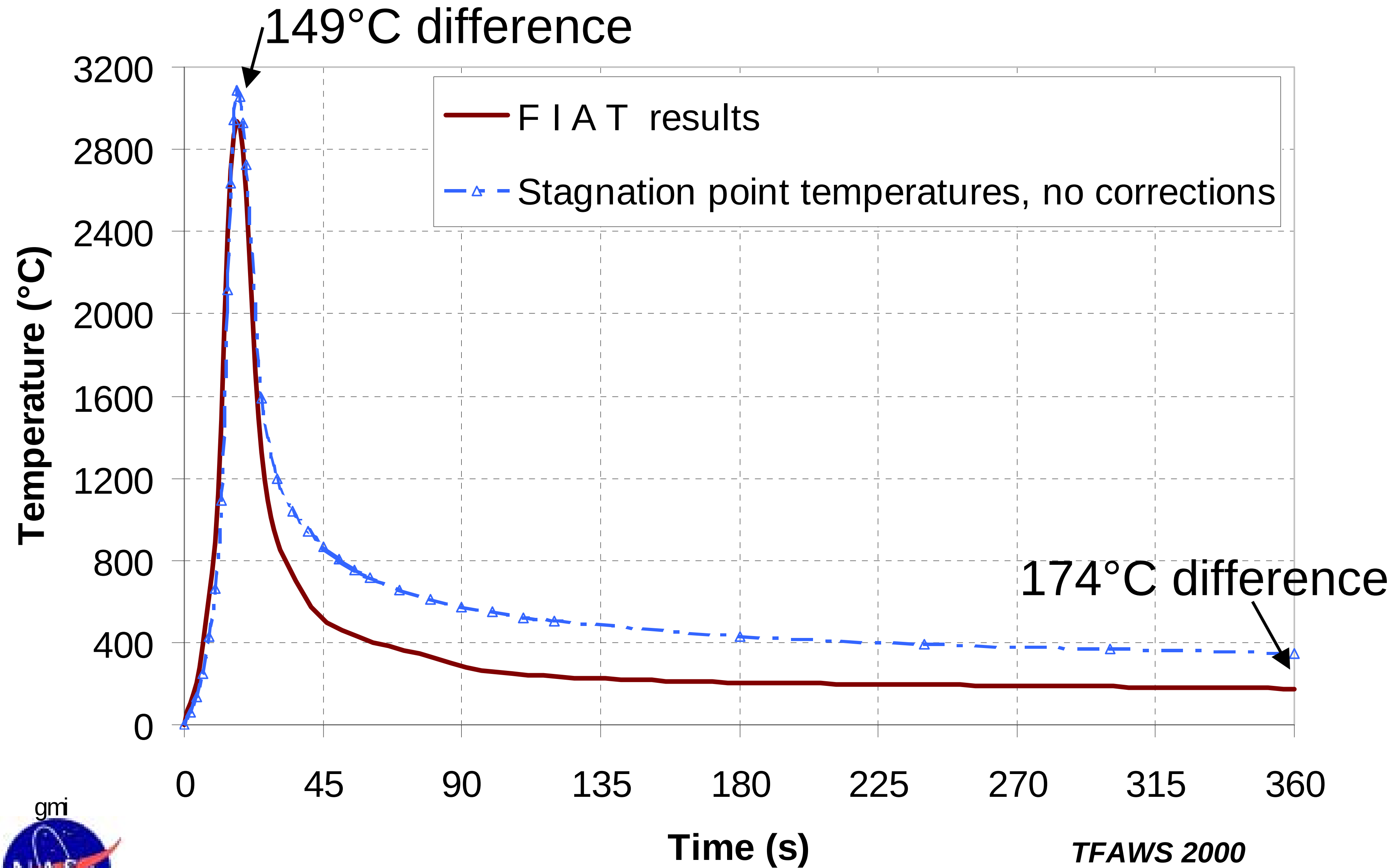
Atmospheric Entry Correlation

- Hot-wall, blowing-corrected heat flux from FIAT applied
- PATRAN thermal analysis does not account for material response
- FIAT material response analysis used to correlate PATRAN model
  - Heat pulse adjusted for mass loss (peaks at 22% reduction) according to:

$$Q_f = \left(A\sin^4 \omega t + B\sin^2 \omega t + C\sin \omega t + D\right) * Q_o$$

  - Char layer properties varied with time
    - Two separate layers with different timing used after 16 s
    - Thermal conductivity, specific heat and density varied with time for char layer
- Similar slight adjustments on afterbody TPS

Atmospheric Entry Results with no Correction



Forebody Entry Results with Corrections

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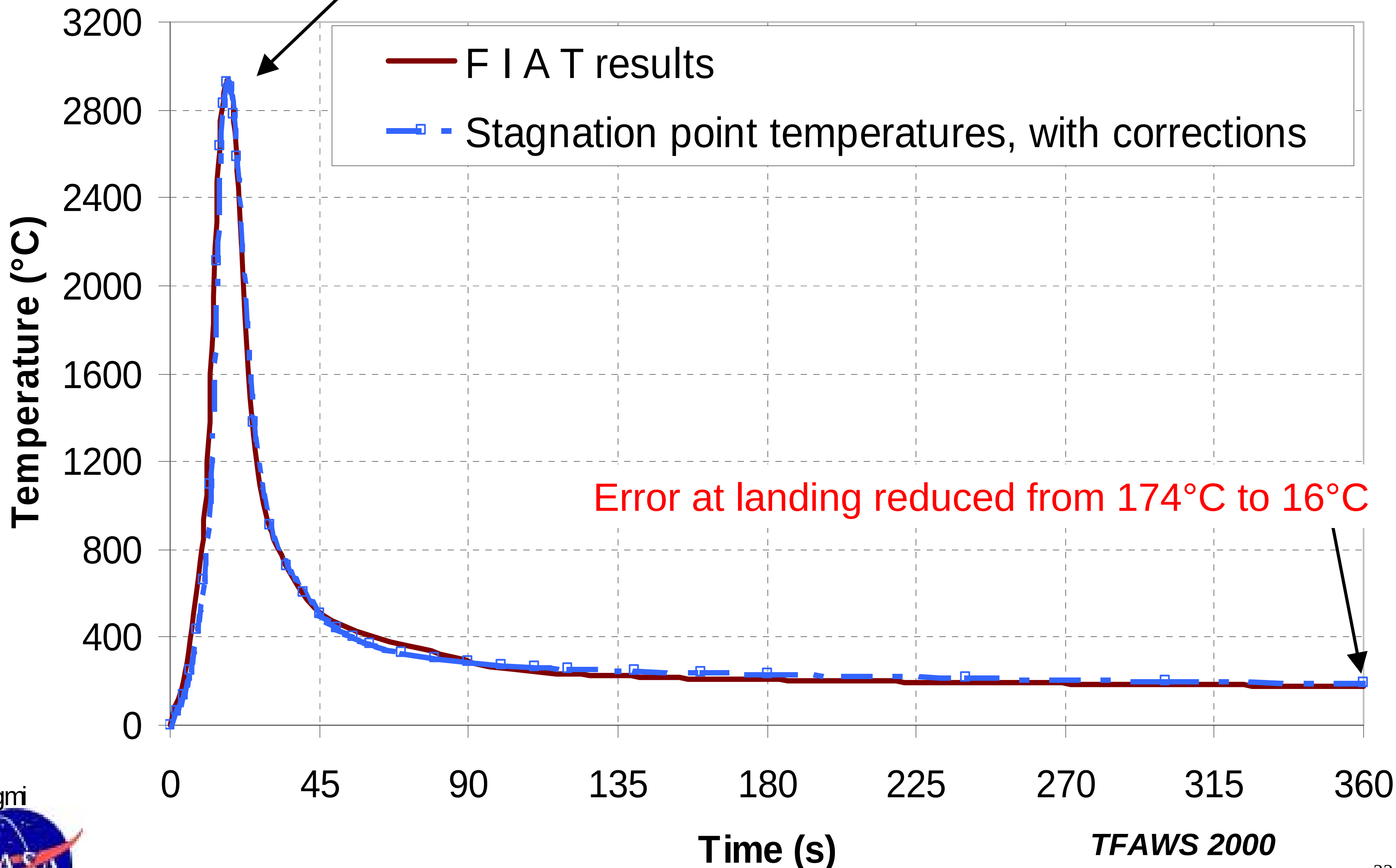
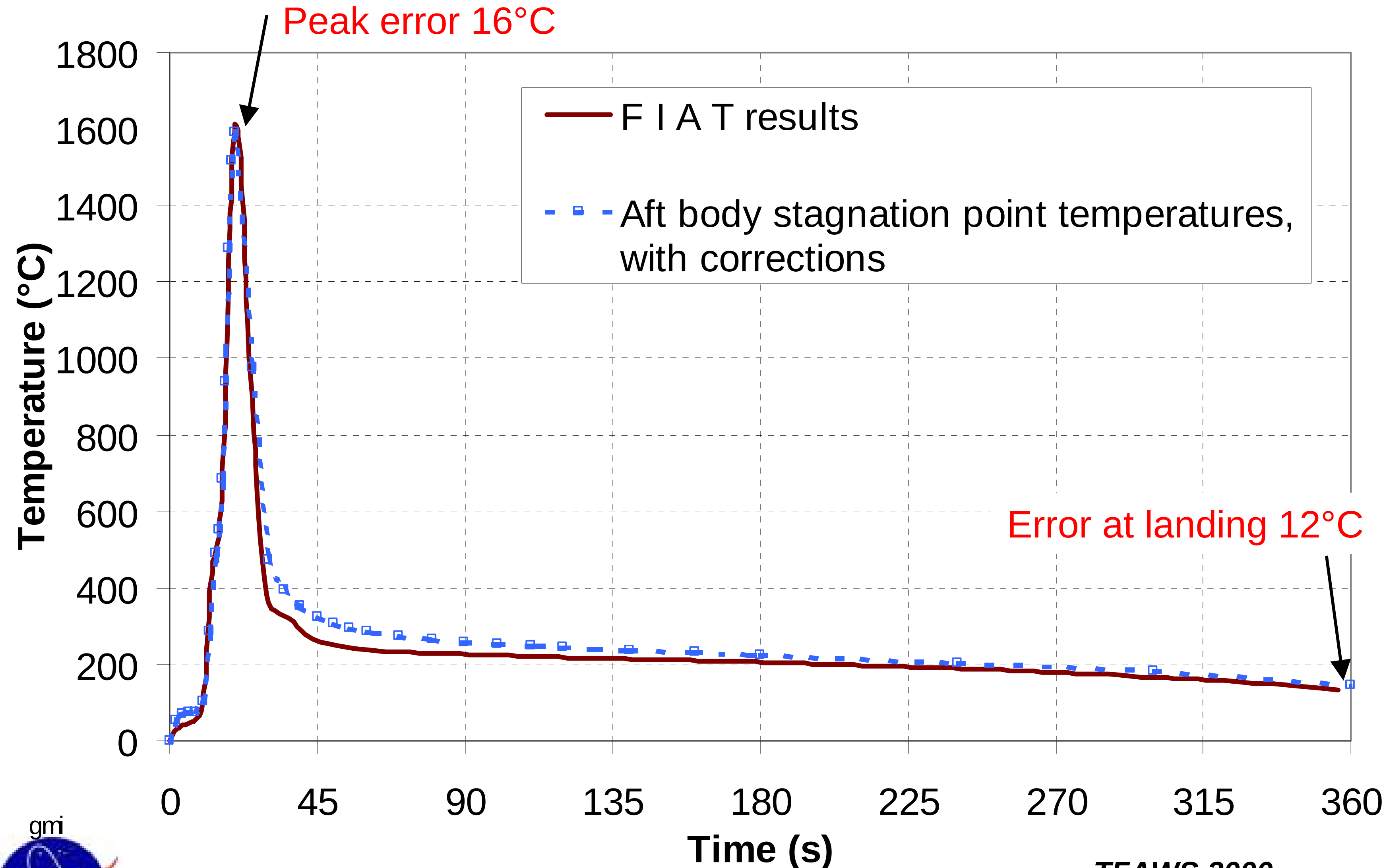
Peak error reduced from 149°C to 12°C



Error at landing reduced from 174°C to 16°C

Aftbody Entry Results with Corrections



Atmospheric Entry Thermal Results (°C)

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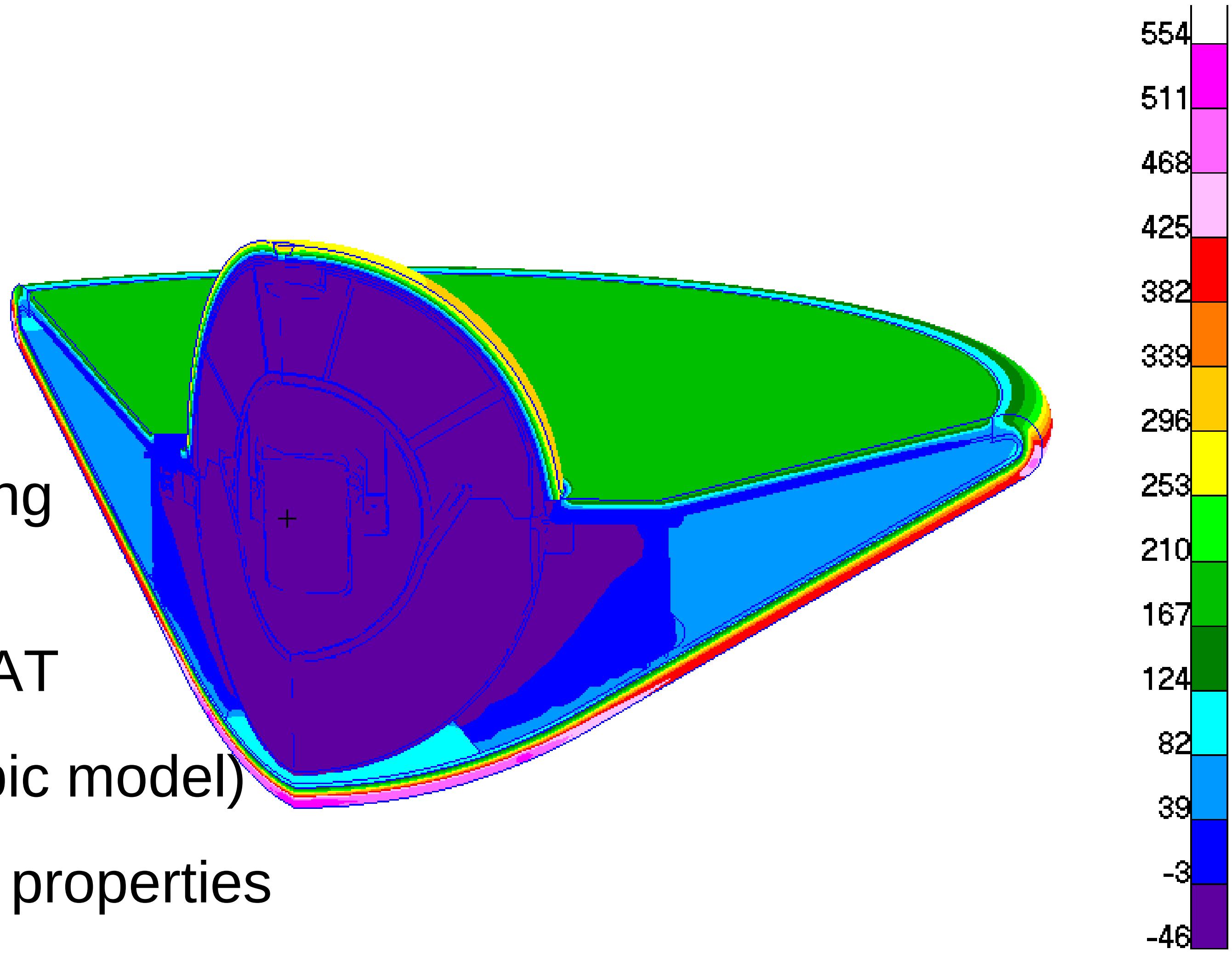


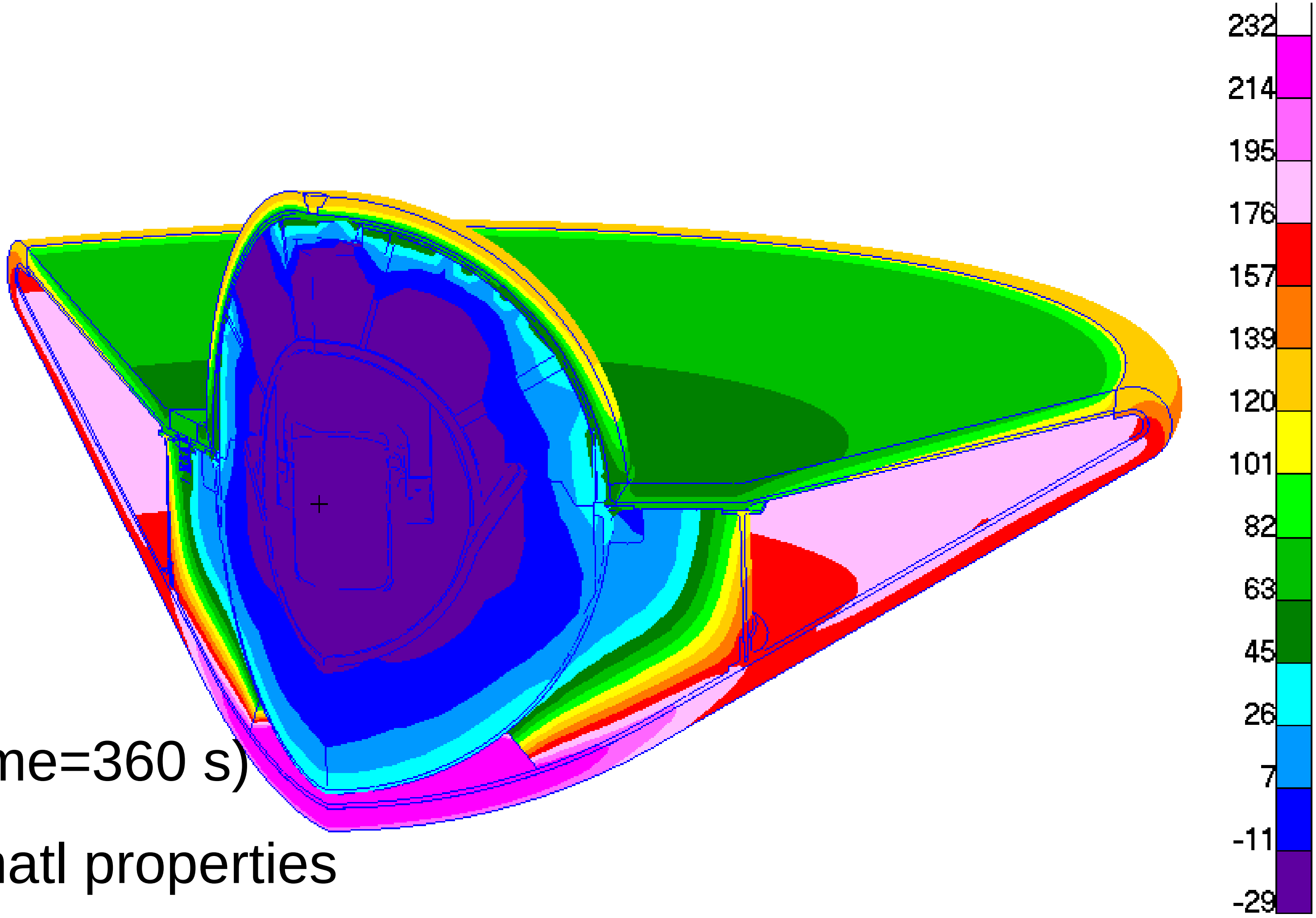
After peak heating (time=45 s)

Correlated to FIAT

(using isotropic model)

Orthotropic matl properties

Atmospheric Entry Thermal Results (°C)



At landing (time=360 s)

Orthotropic matl properties

Comparison of 2D to 3D Properties (°C)

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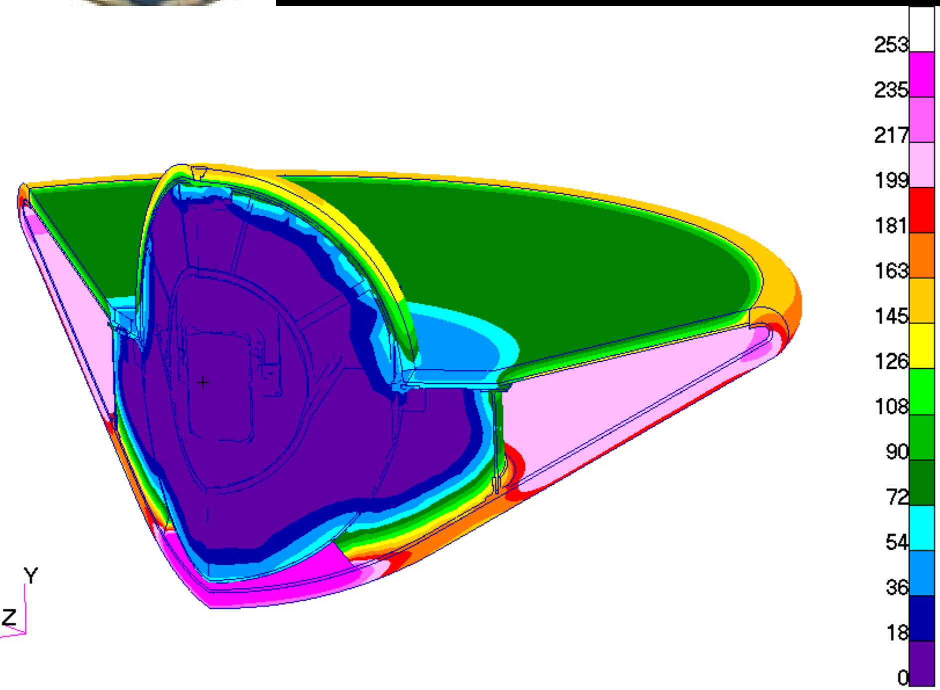
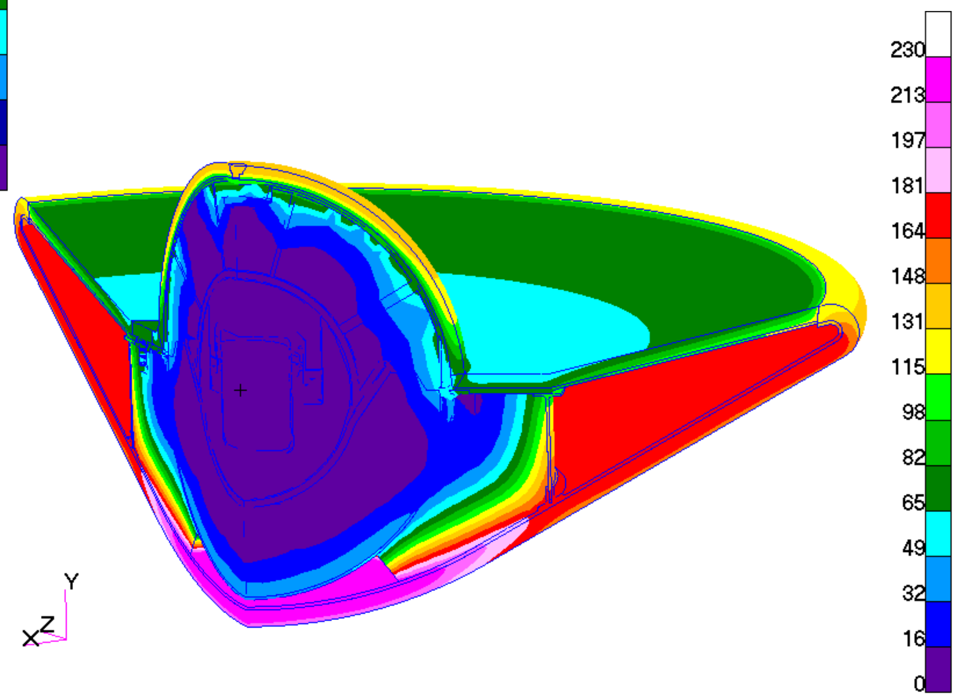


Isotropic properties

Orthotropic properties



Atmospheric Entry Structural Results

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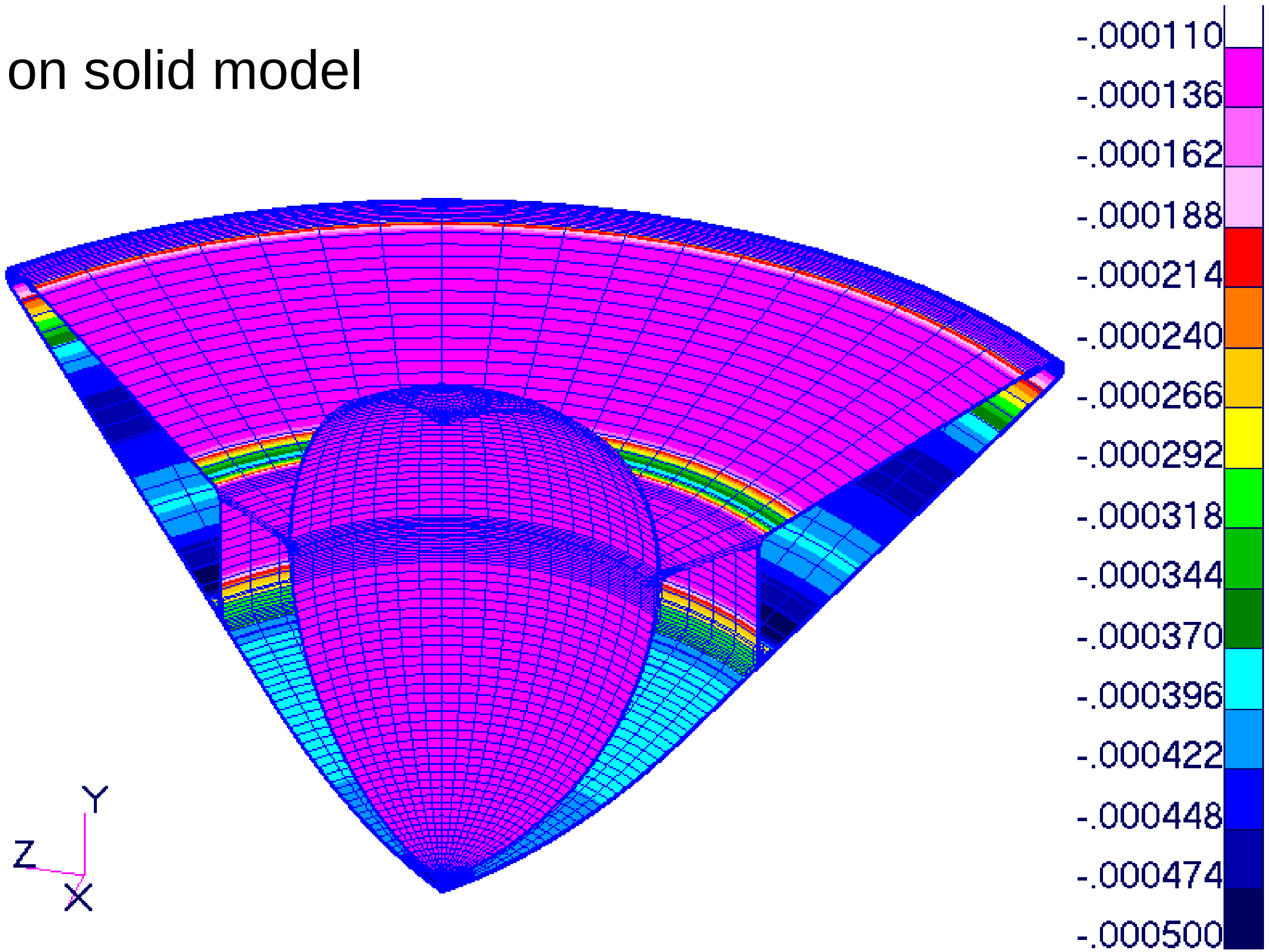
Strains on solid model



Atmospheric Entry Structural Results

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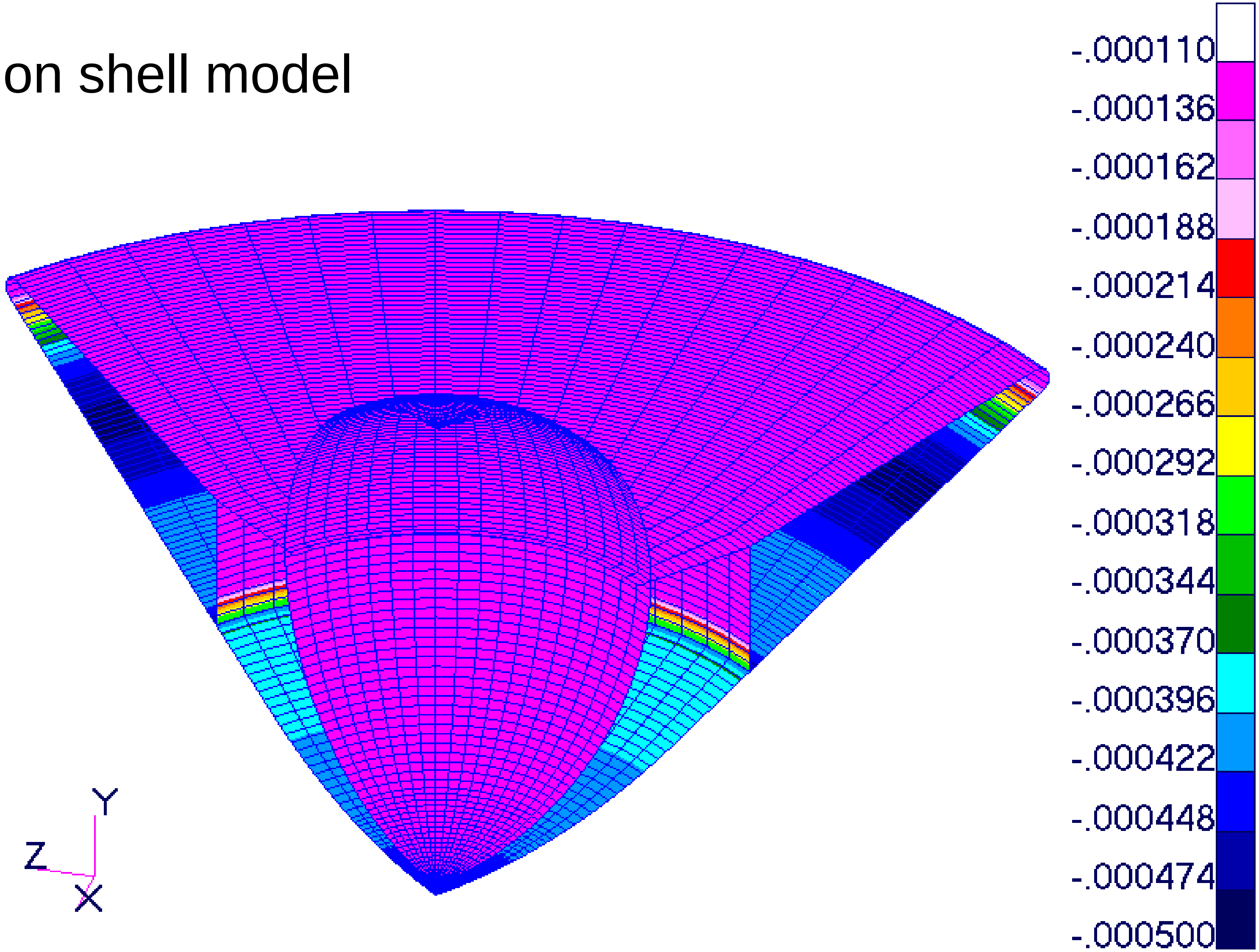
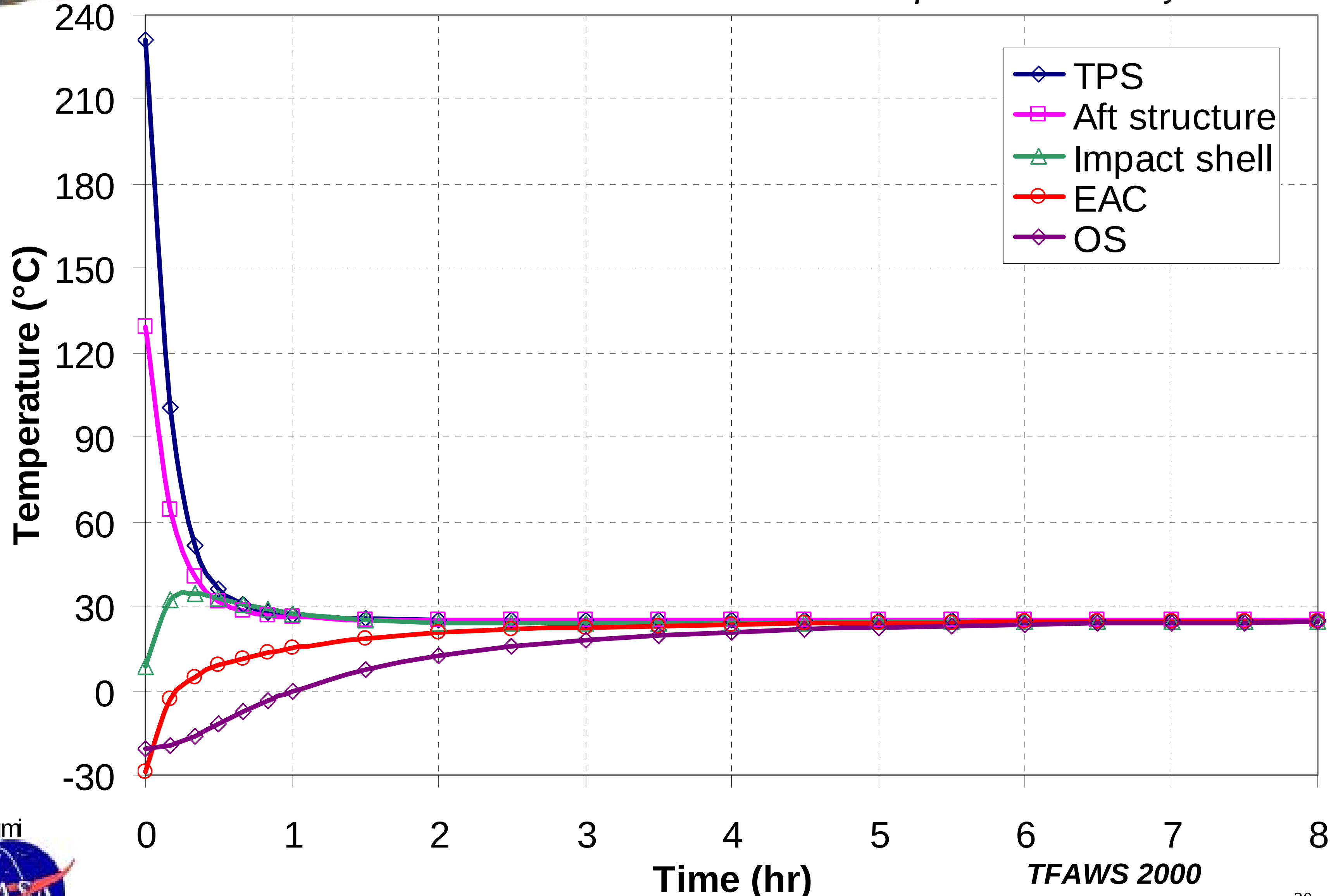
Strains on shell model



Landed Modeling

- Atmosphere at 25°C
- Initial temperatures from last time point of entry
- Radiation and convection to atmosphere
- No ground contact
- Run for 8 hour transient
- OS remains below 25°C

Landed Results



Conclusions

- Integration with geometry:
  - Simplifies 3D analysis process
  - Allows quick response to changes
  - Allows exact geometry modeling
  - Allows model sharing
- Integration with orbital analysis:
  - Dynamic flux and orbit visualization
  - Allows quick response to orbit changes
  - Not complete (duplicate model required)
- Integration with aeroheating and trajectory:
  - Facilitates quick response to trajectory/heating changes

Conclusions (con't)

- Integration with material response analysis:
  - Allows inclusion of multiple material response effects
  - Not complete (only 1D, duplicate model required)
- Integration with structural analysis:
  - Possible even with differing meshes, units, model type
  - Allows precise characterization of vehicle stress state at any trajectory point
- Orthotropic materials applied in complex manner
  - Significant changes in results
- All thermal requirements met

Acknowledgements

- FIAT analysis by YK Chen at NASA Ames
- Aeroheating by Joe Olejniczak at NASA Ames, Neil Cheatwood and Mark Schoenenberger at NASA Langley
- Mechanical design by Steven Hughes and Robert Dillman at NASA Langley